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学位授与の題目	Last Interglacial (Marine Isotope Stage 5) Sea Level and Climate Changes in Southwest Bohol, Central Philippines （フィリピン中部，南西ボホールにおける最終間氷期（海洋酸素同位体ステージ5）の海水準および気候変動）
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学位論文要旨

Abstract

Using a highly accurate α-spectrometric U-series method, we dated some coral reef terraces along the coastal areas of Pamilacan Island, Panglao, and Punta Cruz in southwest Bohol, and reexamined the sea level history during the Last Interglacial. In Pamilacan Island, radiometric dating of successive terraces yielded age groups of 79-83 ky, 101-108 ky, and 122-131 ky, at elevations of 3-4 m, 9-13 m, 20-27 m apmsl, respectively. Based on published mean sea level data of 3-6 m apmsl during MIS 5e, we estimated constant rate of tectonic uplift ranging from 0.18-0.21 m/ky for the past 125 ky. Using these estimates of local uplift rates, paleo-sea levels at 105 ky and 82 ky are calculated to be 9-11 m and 6-9 m below present, respectively. In contrast, elevations of reef terraces correlated with MIS 5e in Panglao and Punta Cruz are only about 13-14 m apmsl and 5c terraces if not absent, are poorly developed. In one of the sites surveyed in Panglao, heights of the 5c and 5e terraces are only 5 m and 13 m, respectively. Here, local uplift rates since MIS 5e are much lower, about 0.06-0.09 m/ky and estimate of 5c mean sea level is a few meters (1-3 m) below present. Variation in the uplift rates and paleo-sea levels within these three neighboring islands is probably related to localized activity of tectonic structures that caused vertical displacements in the flight of terraces in Pamilacan.

Skeletal oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes were also measured from *Porites* corals. These samples were acquired from Last Interglacial uplifted marine terraces in southwest Bohol, and were correlated to MIS 5e, 5c, and 5a. The $\delta^{18}O$ -Sea Surface Temperature (SST) relationship show cooler conditions during the Marine Isotope Stage (MIS) 5e by *ca.* 4°C relative to present and fluctuates about 1-2°C during the high-stand events of MIS 5. These apparent low SST values are probably the result of enhanced insolation seasonality during the Last Interglacial maximum. Such cooling is highly unlikely as the minimum temperature record during that time is 21.5°C which is close to the lower thermal limit of coral growth of 18°C. The coral $\delta^{18}O$ primarily reflects combined effects of local oceanographic and climatic variability which is largely determined by sea levels, run-off events, and intensified trade winds resulting to increased equatorial upwelling and equatorward flow of cold water.

Keywords: Last Interglacial (Marine Isotope Stage 5), Bohol, α-spectrometric U-series dating, skeletal oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes, sea level

I. Introduction

High-resolution studies of past sea level fluctuations and climatological variations extending beyond the past few decades are important for establishing natural baseline of variability for successful prediction of future behavior of the sea surface and. The peak of the Last Interglacial period (*ca.* 130-110 ky ago) is important since it is considered to be an analogue of the present interglacial. At that time, global sea level was at least 3 m and probably more than 6 m higher than the present sea level with climate as warm as or warmer than today. Moreover, because of the abundance of evidence which can be accurately dated, the Last Interglacial stage serves as the best available interval to study the processes and changes that occurred during that time.

Exposed coral reef terraces along the coastal areas of southwest Bohol were dated using a highly accurate α-spectrometric U-series method (Fig. 1). The results were augmented with the data from previous work to re-interpret the sea level history in southwest Bohol during the Last Interglacial or the marine oxygen isotope stage (MIS) 5. It is also the aim of this paper to investigate the implications of such sea level variations on the tectonic setting of the study area. This study is the first attempt to date fossil corals from the marine terraces in Pamilacan Island.

Likewise, this paper presents one of the first studies on $\delta^{18}O$ and $\delta^{13}C$ paleothermometry derived from *Porites* corals that grew during the Last Interglacial or the MIS 5 in Bohol, Philippines. The availability of corals representing the isotope substages 5e, 5c, and 5a provide a high-resolution record of climate fluctuations, at an interval of about 25 ky, during the Last Interglacial period. Moreover, the study area is ideally located in the western equatorial warm pool which principally modulates global climate. The data are used to investigate whether the sea surface temperatures (SSTs) varied during the substages of the MIS 5 at this tropical site. The acquisition of these new data are valuable since more accurate estimates of the past $\delta^{18}O$ distribution in tropical surface waters is crucial to establishing the role of the tropical climate in global climate change.

II. Methods

$^{230}Th/^{234}U$ ages were determined at Kanazawa University using established chemical and α-spectrometric procedures previously described in Omura *et al.* (2004). The 1σ precision is generally ≤2% or ≤2 ky for Last Interglacial samples, achieved through α-counting within a period of 21-30 days. Pretreatment of samples and measurements of the stable isotopes $\delta^{18}O$ and $\delta^{13}C$ were conducted at the National Institute of Advanced Industrial Science and Technology (AIST). The method of sample processing for isotope analysis is described in Suzuki *et al.* (1999, 2000, 2003) and Gagan *et al.* (1994, 1996, 1998).

III. Discussion and Conclusions

The α-spectrometric U-series dates of fossil corals from raised marine terraces in Pamilacan Island, supplemented with new and reported dates from the neighboring islands of Panglao and mainland Bohol, presented a more comprehensive picture of sea level changes in southwest Bohol during the Last Interglacial. In Pamilacan Island, coral reef terraces correlated to MIS 5e, 5c, and 5a were found to have ages of 79.2±1.5-83.2±1.2 ky, 100.7±1.5-107.9±1.5 ky, and 121.5±2.0-130.8±9.4 ky, respectively (Fig. 2). These terraces contain the only record of 5a coral reef limestone deposits in all the sites surveyed in western Bohol. Two distinct uplift rates were recognized within the study area (Fig. 1c). In Pamilacan Island, constant rate of uplift in the past 125 ky range from 0.18-0.21 m/ky while estimates from San Isidro (Panglao Island) and Punta Cruz are between 0.06 and 0.09 m/ky. At Pamilacan, sea levels associated with 5c terraces are –6 to –9 m while that of 5a are –9 to –11 m. At San Isidro and Punta Cruz, the MIS 5c paleo-sea levels are estimated to be -1 to -3 m (Fig. 2). Differences in estimates of uplift rates and 5c paleo-sea levels between the three neighboring sites suggest that local tectonic activities may have greatly influenced higher vertical displacements recorded in the marine terraces of Pamilacan Island.

Geochemical records of SSTs were generated from the $\delta^{18}O$ and $\delta^{13}C$ compositions of fossil corals that grew during the marine substages 5e, 5c, and 5a as well as the Late Holocene period (Fig. 3). The seasonal variations in the $\delta^{13}C$ values of the fossil corals probably resulted from algal photosynthesis that causes ^{13}C enrichment (higher $\delta^{13}C$ values) of the internal calcification reservoir from which skeletal carbon is drawn combined with increased seasonal contrast in insolation. During the peak of the Last Interglacial (MIS 5e) mean $\delta^{18}O$ values for two 5e samples range from 24.1-25°C which reflect a cooling of about 4°C relative to present SST of 28.6°C. SSTs fluctuated from relatively warm (27.4°C) to cooler (26.3°C) conditions from substages 5c to 5a before finally reaching a temperature of 27.0° C in the Late Holocene. The general pattern of SST oscillations since the MIS 5e up to present shows a shift from lower to higher temperatures. This cooling recorded by the fossil coral likely reflects a significant change in the $\delta^{18}O$ of seawater. Intensified trade winds and the resulting increased equatorial upwelling together with equatorward flow of cold water will produce a relatively large decrease in SST in the western equatorial Pacific. A drop in SST can also be attributed to lower sea level and increase freshwater input in the ocean. This is reflected in the $\delta^{18}O$ values of the 5c and 5a coral samples when sea level fell from 1-3 m to 9-11 m below present, respectively. Contrary to the other studies that show warmer temperatures during the peak of the Last Interglacial, corals from Southwest Bohol may have recorded enhanced effects of local environmental conditions rather than globally-induced climate variations.

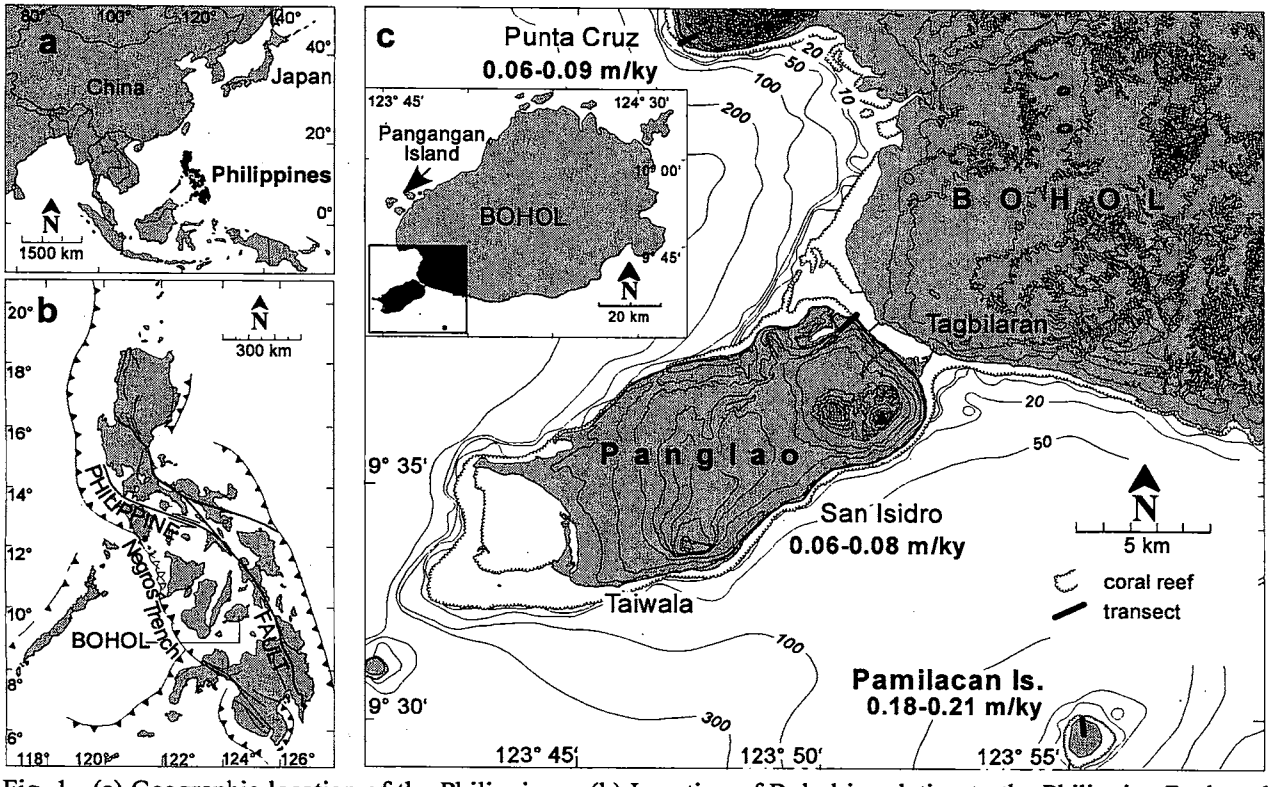

Fig. 1. (a) Geographic location of the Philippines. (b) Location of Bohol in relation to the Philippine Fault and the Negros Trench, the two tectonic structures that most influence the relative stability of Bohol. (c) Positions of profiles and samples along with local uplift rates in the past 125 ky estimated from dating uplifted marine terraces.

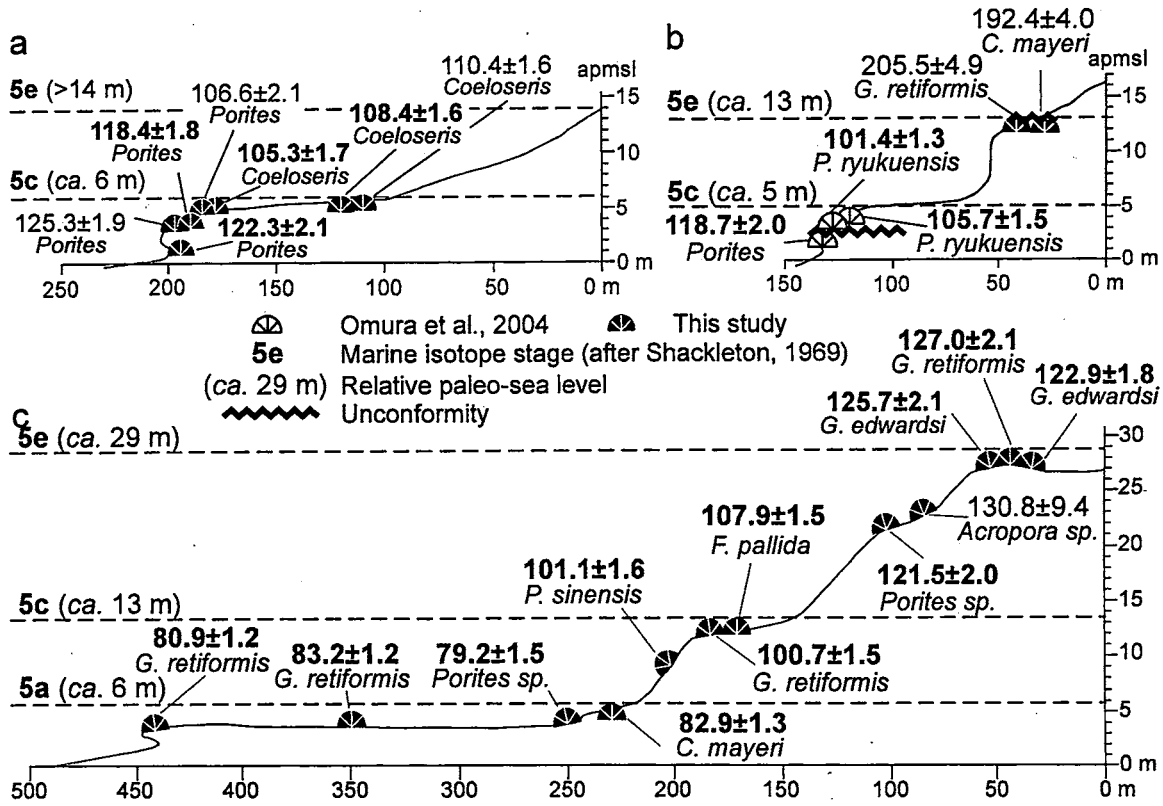

Fig. 2. Profiles of marine terraces along the coasts of (a) Punta Cruz Point, (b) San Isidro, and (c) Pamilacan Island showing the radiometric dates and estimates of relative sea levels. The U-series dates of the corals and the morphology of the terraces at Punta Cruz and San Isidro confirm the presence of terraces correlated to MIS 5e and 5c. In Pamilacan Island, three-step well-preserved reef terraces are associated with isotope substages 5a, 5c, and 5e. Except for 2 *Porites*, almost all of the corals sampled in this locality yielded highly reliable dates providing a remarkable record of sea level changes representing warm intervals or high sea stands during the MIS 5.

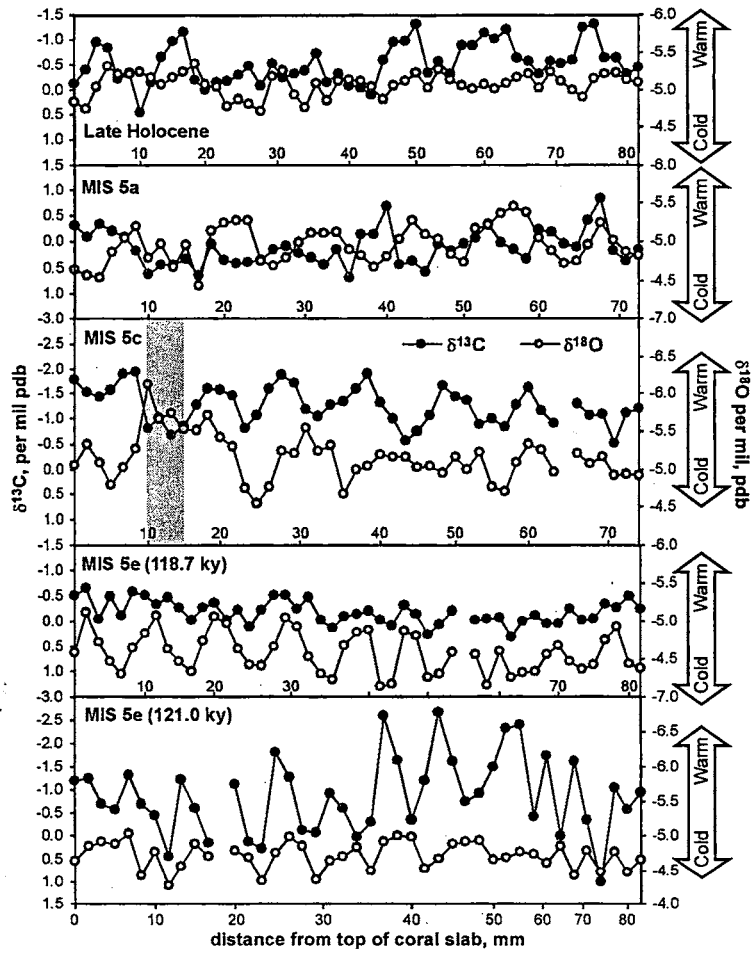

Fig. 3. Comparison of stable carbon and oxygen isotopic compositions of Late Holocene and Last Interglacial *Porites* corals. MIS 5c sample shows growth disturbance between 10-15 mm (shaded area) as indicated by the unusual patterns of the oxygen and carbon isotope ratios. Hence, this portion is not included in the examination of $\delta^{18}O$-temperature relationship. The d18O values recorded in the fossil corals shows an apparent cooling during the MIS 5e which is consistent with the results of Suzuki *et al.*, (2001) based on the skeletal $\delta^{18}O$ record of corals from Ryukyu Islands, Japan. It was suggested that lower SSTs likely reflect a significant change in the $\delta^{18}O$ of seawater rather than a large cooling.

学位論文審査結果の要旨

平成16年7月28日の学内委員による第1回審査会と，8月3日の外部審査員を含む審査員全員が出席して行った口頭発表会終了後の第2回審査会で協議を行い，以下の結論に達した。

本論文は，主として，ヴィサヤス地方のボホール島から19km南方に位置するパミラカン島で発見したサンゴ礁段丘について，精密地形測量とウラン系列年代測定の結果を系統的に記述するとともに，過去80.0～125.0ky間の同地域における海面変化と地殻変動史を論じたものである。その中で，上記の段丘を，最高地点高度が27m，内縁高度が，それぞれ13mと6mの平坦面を有する3段に区分し，最終間氷期（MIS-5）における3回の相対的高海面期（MIS-5e，-5cおよび-5a）に形成されたことを明らかにした。そして，MIS-5e（125ky）における海面高度（3-6m）と以降の垂直変動の等速性（0.18-0.21m/ky）を仮定することで，MIS-5c（105ky）および5a（82ky）のパミラカン島周辺域における海面高度が，それぞれ，現在より9-11mと6-9m低かったとの結論を導いた。また，ボホール島南西域で採集したハマサンゴ化石の酸素同位体比測定結果から，MIS-5における調査地周辺海域の表層海水温等についても言及した。このような研究成果の中でも，特に，フィリピン諸島から初めて，MIS-5cと-5a当時の海面高度をセットで解明した点は，西太平洋活動縁辺域の広域に及ぶ地殻変動史の解明に一石を投じたものとして高く評価できる。

以上の審査結果を総合して慎重に審議し，本論文は博士（学術）に値すると判定した。